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SOLAR-SYSTEM TESTS OF GRAVITATIONAL THEORIES

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Progress

We are engaged in testing gravitational theory by means of observations of objects in the solar system. This work tests the equivalence principle (EP), the Shapiro time delay, the advances of planetary perihelia, the possibility of a secular variation \dot{G} in the “gravitational constant” G , and the rate of the de Sitter (geodetic) precession of the Earth-Moon system. We describe here the results under this contract.

Progress has been made primarily on two fronts, improvement of our solar-system model and acquisition of additional data for analysis. Our solar-system model is implemented in a computer program called the Planetary Ephemeris Program (PEP). We recently extended the PEP model of Earth nutation with adjustable correction terms at the principal frequencies; it now covers planetary radar observations in addition to the other types of data. We also refined our model of tidal drag in the motion of the Moon. In turn, these changes have required a complete reanalysis of the data, still underway. The impact of these enhancements on our parameter estimates appears to be relatively small compared to the standard deviations. In fact, it is our objective to make model enhancements before their absence has a significant effect on our analysis. The inclusion of additional data, primarily from the ongoing programs of lunar laser ranging (LLR) and planetary radar ranging, has made greater changes. The accumulation of LLR data, in particular, has increased the power of that data set such that it now outweighs the planetary data in our studies of \dot{G} . Indeed, during the course of this contract, we have added about 5,000 new (and superior) LLR measurements to the analysis, leading to a decrease of more than four-fold in the statistical standard deviation in our estimate of \dot{G} .

Our results to date are consistent with the predictions of general relativity. We list here the current values and the standard deviations (including systematic, not just statistical, errors) for the relevant parameters: 1×10^{-2} for the fractional relativistic contribution to the perihelion advance of Mercury, 1×10^{-3} for Nordtvedt’s η parameter, 2×10^{-2} for the metric parameter β , 2×10^{-3} for the metric parameter γ , 1×10^{-2} for h (the coefficient of the de Sitter precession), and $1 \times 10^{-11} \text{yr}^{-1}$ for \dot{G}/G .

One of the parameters of our model is a coefficient for the correction to the rate of atomic clocks on Earth due mainly to the annual variation of the Sun-Earth distance (and, thus, the gravitational potential experienced by the clocks, as well as their velocity). This gravitational redshift of terrestrial clocks largely cancels in two-way observations like radar or laser ranging, since the transmitting and receiving systems experience very nearly the same redshift. However, pulsar timing measurements constitute comparisons between widely separated clocks and thus can provide a test of the gravitational redshift prediction. We performed an analysis of the combination of pulse timing data for the single pulsar B1937+21 in order to make such a test. Preliminary sensitivity studies indicated that the test should determine the redshift coefficient with an uncertainty approaching one part in 10^3 , but our results proved otherwise. We discovered that the uncertainties in the alignment of the planetary and radio reference frames are not sufficiently overcome with only one pulsar as a reference point; the study involving only B1937+21 fell short by an order of magnitude. For that reason, we plan to include additional pulsars in the analysis. Therefore, in order

to model pulsar timing data in general, we have expanded our pulsar model to include the effects of multiple companions in elliptic orbits. In particular, B1257+12 is not only timed near the microsecond level, but is only 17 degrees from one of the two directions of the minor axis of the Earth's orbit. (Because of the annual periodicity of both the gravitational redshift and the timing signature of any error in the pulsar's position, the minor axis offers two favorable directions on the sky where the signatures are exactly out of phase. Including any pulsar very near either of these directions significantly improves the sensitivity of the redshift test.) Because B1257+12 is known to have planets, our recently-added model of pulsar companions in elliptic orbits is a necessary step in the enhanced redshift test. In the end, it may be necessary to refine that model to include numerically-integrated orbits accounting for the mutual perturbations of those planets.

Plans

In the near future, we plan to complete the reanalysis of the entire collection of data using the improved solar-system model and publish the results.

With additional data, we may achieve a realistic uncertainty significantly below $10^{-11}yr^{-1}$ for \dot{G}/G , and thus make an important contribution to the understanding of cosmology in view of the ongoing attempts to improve the estimate of the Hubble constant H_0 and its interpretation as a measure of the age of the universe.

In addition, we plan to augment the equations of motion in PEP to include a possible departure from the inverse-square law of Newtonian gravitation, by making the effective gravitational "constant" a function not only of time (as in the formulation of \dot{G}), but also of distance. There have been a number of attempts to detect such a departure on Earth, and, although no such effect has yet been detected, the solar-system scale provides a whole new regime to investigate.